# Some Preliminary Results from a Programme of Flight Research with a Low Reynods Number Aircraft

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## Introduction

This paper presents some wind tunnel and early flight test data from a programme of research with human powered aircraft. Airglow first flew in July 1990 and since then has been used as a platform for investigating the aerodynamics of low speed aircraft. It has been flown at Duxford Airfield at RAe Bedford and at Mindelheim in Germany. A sketch of the aircraft and instrumentation is shown in figure 1.

Bussolari, [2] and Jex [3] detail some results obtained with the Daedalus and Gossamer Albatross aircraft's. However apart from this there is very little data on the performance of low speed aircraft, this shortage of information is a real problem for designers. A comparison of other HPA power polars is shown in figure 2.

Our primary objectives have been to measure the aircraft's power polar and airfoil profile drag. The power polar is deduced from the aircraft's total energy. Airspeed, altitude and drag are measured continuously and used to calculate the instantaneous power. The pilots power output is measured with a drive shaft mounted load cell. The profile drag is measured using a hot wire anemometer traversed through the wake of the wing.

## Instrumentation

All data are sampled at 32 Hz and stored on a 10 bit 8 channel data logger or a portable PC for subsequent analysis.

Airspeed is measured using a propeller anemometer this has been calibrated under steady conditions. However it will have errors which can be as high as 15% under unsteady conditions due to over speeding (the propellers inertia) and blade stalling. Hence we are currently developing a lightweight ultra sonic anemometer to reduce possible errors to a minimum. (These instruments are capable of measuring airspeed to within 1 mm/s over a speed range of 60 m/s and can respond to gusts at frequencies up to 20 Hz.)

An ultrasonic altimeter measures the aircraft's distance from the runway to within 0.5 cm. This uses a Polaroid transducer, chip set and PIC micro processor to output a calibrated voltage for the data logger.

The thrust (and hence drag) needed to fly is measured using a small i.c. engine mounted so a stain gauged strut in tension sends a filtered signal to the data logger. This is shown in figure 3. It was necessary to low pass filter the signal to remove vibration from the engine. This system worked well and allowed the pilot to fly very smoothly. The throttle and a fuel shut off were operated by small rc servos hard wired to the controls. However we worried about the effects of vibration on the light CFRP structure of the aircraft and if we were doing this again would use an electric motor.

The pilots power output is calculated from simultaneous measurements of torque and rotation rate of the drive shaft. Torque is measured with a drive shaft mounted load cell and the signal is transmitted through a pair of slip rings to the data logger. The load cell was carefully designed to decouple it from flexure of the drive shaft and aircraft which would otherwise contaminate the data. Figure 4. shows a short sample of data taken during take off. (The main reason that some cyclists use elliptical chain rings is to attempt to smooth out the large fluctuations in torque and power that occur twice per revolution of the pedal cranks.)

The wings profile drag is measured with a hot wire anemometer and wake traverse mounted on the trailing edge of the wing. We decided to develop our own anemometer because we needed a lightweight battery operated instrument and because of the prohibitively high cost of commercial systems. This turned out to be a difficult task taking many hours of work however we recently compared the home made anemometer with a DISA M01 constant temperature anemometer and found that it has about half the noise. It will operate with standard wires and films up to a resistance of 50 Ohms and the bridge is compensated for a 5m probe cable. The schematic, circuit board layout and component details for the anemometer are given in appendix A for anyone wishing make a copy of the anemometer.

**A new analogue airspeed display**

Nick found the digital displays of the airspeed indicator Bryan made and the Skywatch ASI difficult to read. We spent a lot of time thinking about a display that would be easy to read. What we eventually made was a graphical ASI, the aircraft's power polar is displayed as an x-y graph using coloured light emitting diodes. Green for minimum power and red as the airspeed drops towards the stall. We found that you can see, without thinking, exactly how fast you are flying. Since it is micro processor controlled it is easy to reprogram for changes in pilot weight.

**Wind tunnel Data**

A full size wing panel was fabricated with the same structure and materials used on the aircraft. The test panel used the DAI1335 airfoil section, had a span of 2m and a chord of 1.05m. The section accurately reproduced the surface finish and accuracy of the aircraft's wing. Richard Lean carried out two sets of experiments in the first the section was mounted vertically in the low turbulence tunnel and boundary layer profiles where made at a number of chord wise stations and angles of attack. Some of this data is plotted in figure 8. against output from Mark Drela's XFOIL code which was used to design the section.

In the second set of experiments the section was mounted horizontally in the Markham tunnel and the drag polar was measured using the wake traverse. The wing section is large so Richard wrote an inviscid panel code to simulate the interaction between the section and the tunnel. This allowed him to position the section to minimise interference effects and to determine the range of angles of attack over which the pressure distribution on the wing section would be sufficiently undisturbed for the data to be valid. One of the drag polars he obtained is shown in figure 9. The data shows pleasing agreement with the modelled data. (The modelled and measured polars diverge at angles of attack above 6 degrees as the section begins to interact with the tunnel.) He has shown that we can use codes like XFOIL to design human powered aircraft sections and provided we take care in their construction they will perform as expected.

**Flight Data**

Since it is impossible to fly the aircraft at constant altitude and airspeed the aircraft's power must be deduced from its total energy, airspeed, altitude (corrected for the slope of the runway) and power input or drag are recorded simultaneously. The measured power can then be corrected for changes in kinetic and potential energy.

The aircraft was first flown with all the instrumentation working on the 16th January 1996 and since then on another four occasions during the year. We experienced many difficulties with the instrumentation. For example the altimeter had to be completely redesigned using a Polaroid transducer and sonar ranging chip set. Hence we have not yet collected enough good data to completely measure the aircraft's power polar. However what we have is consistent with the aircraft's predicted performance. We have plotted some of this raw data to show that the techniques work.

Figures 10 and 11 show the pilots power output and airspeed during a short flight for comparison with the aircraft's calculated power polar, Fig 12. (The power polar has been factored by the propeller and drive train efficiencies for direct comparison with the data taken from the load cell.) Changes in the aircraft's altitude and airspeed have not been allowed for in these plots.

**Afterthought**

We are often asked why we built a human powered aircraft and what the use of it is. The first answer is because it was fun, we enjoyed ourselves and made some good friends.

We started this work with no knowledge of instrumentation and no idea of how hard it is to get good data. We thought that if Dr Who could build a trans-dimensional flux damper in less then one episode that what we wanted to do would be simple. (Or something like that.) Later I found out that in a university it takes several post docs and technicians three years to develop an instrument and then it usually doesn't work, at least at first.

I got an account with an electronics company and started setting fire to op amps. We learnt - mostly thanks to the patience of Bryan Gostlow who (usually) managed not to laugh to much. The hot wire anemometer has been used for turbulence research.

We found that building a human powered aircraft opened opportunities that we never expected when we started. We earned respect without intending to but most importantly made good friends.

**Acknowledgements**

The construction and flight testing of Airglow where funded with Grants from the Human Powered Aircraft Group of the RAeS. None of this would have been possible without the good humoured work of the rest of the team. Mark McIntyre, Nick Weston, Bryan Gostlow and  Professor Gastor who gave encouragement and much useful advice to us.

**References**

1. Bussolari, S.R. Langford, J.S., and Youngren, H.H. 'Flight Research with the MIT Daedalus Prototype', SAE Paper #871350, June 1987.

2. Jex, H.R. and Mitchell, D.C., 'Stability and Control of the Gossamer Human Powered Aircraft by Analysis and Flight Test'. NASA CR-1627. November 1982

3. Lean, R.M., 'Wind Tunnel Testing a Low Reynolds Number Airfoil', Fourth year project 1996/96. Cambridge University Engineering Department.

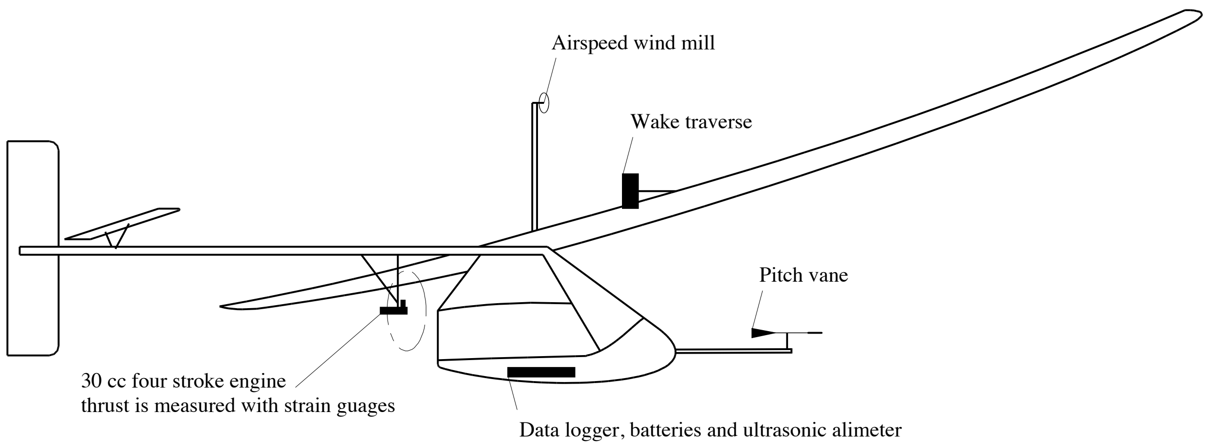



Figure 1. Airglow HPA instrumentation

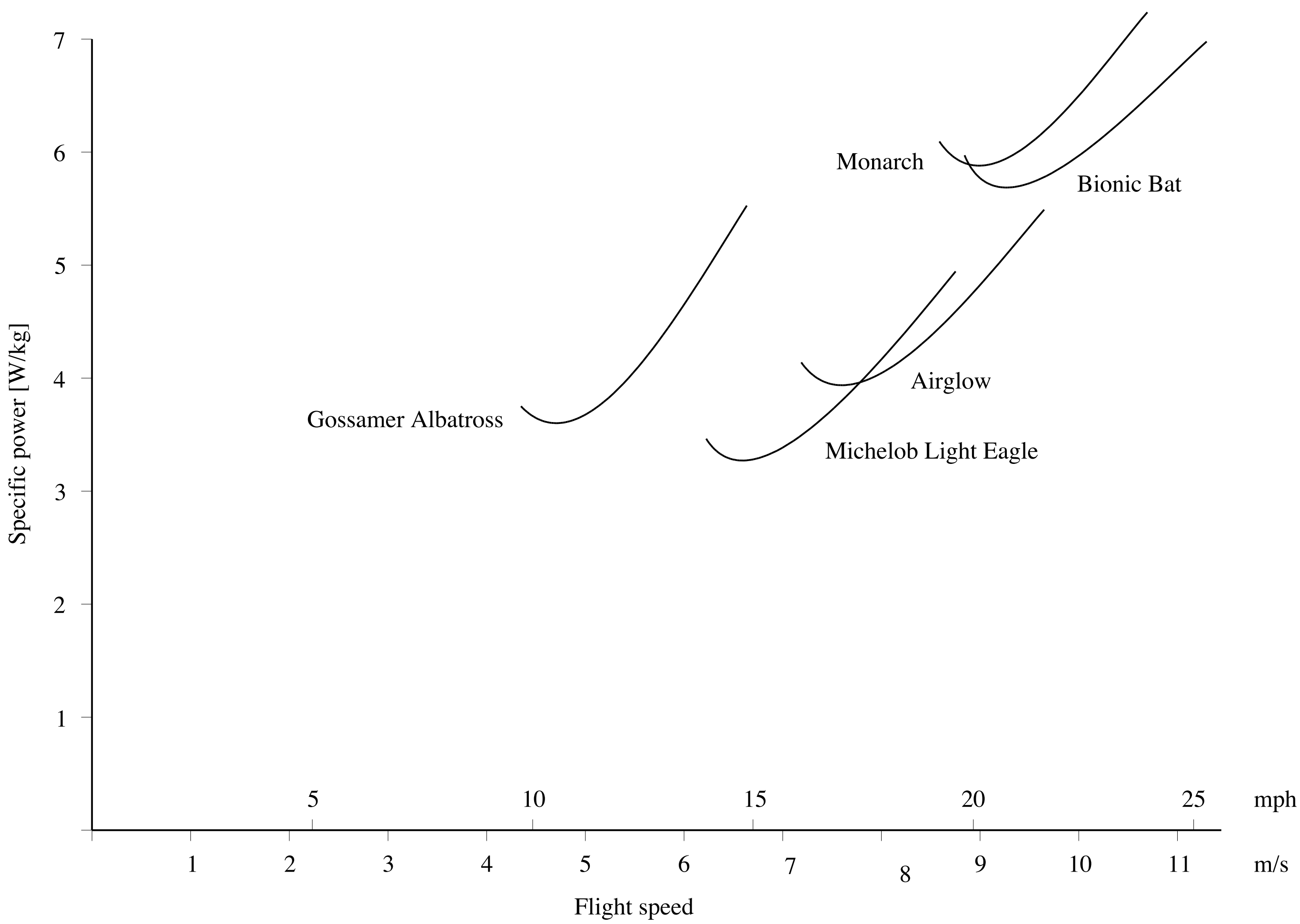



Fig. 2. Power polars for some human powered aircraft


Figure 3. Airglow HPA flying with a small i.c. engine mounted using a strain gauged strut to measure thrust in flight.

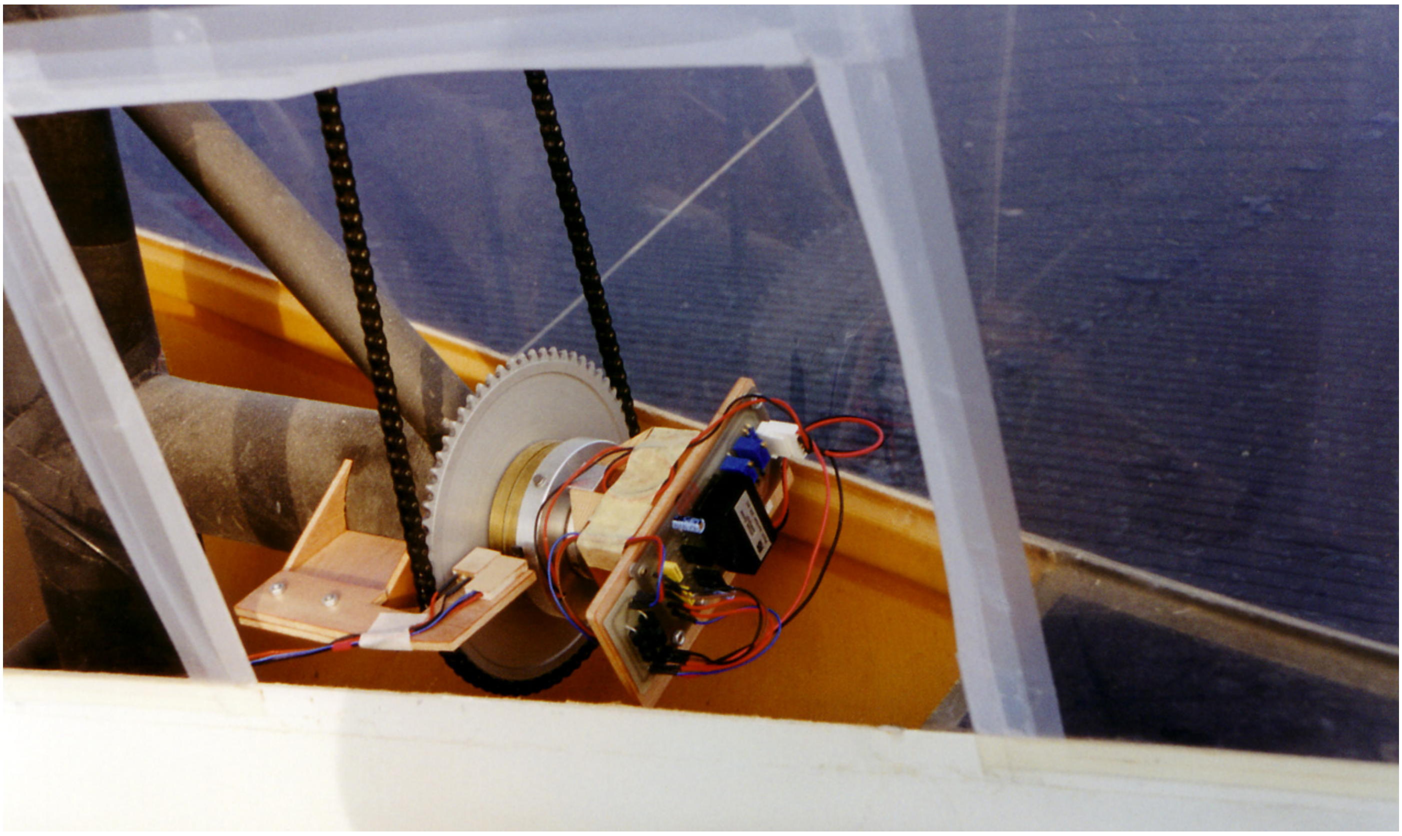


Figure 4. A strain gauged beam at the end of the drive shaft is used to measure torque and hence power input in flight. The voltage signal is sent through slip rings to a data logger. Rotation rate is measured with a hall effect sensor and magnet.

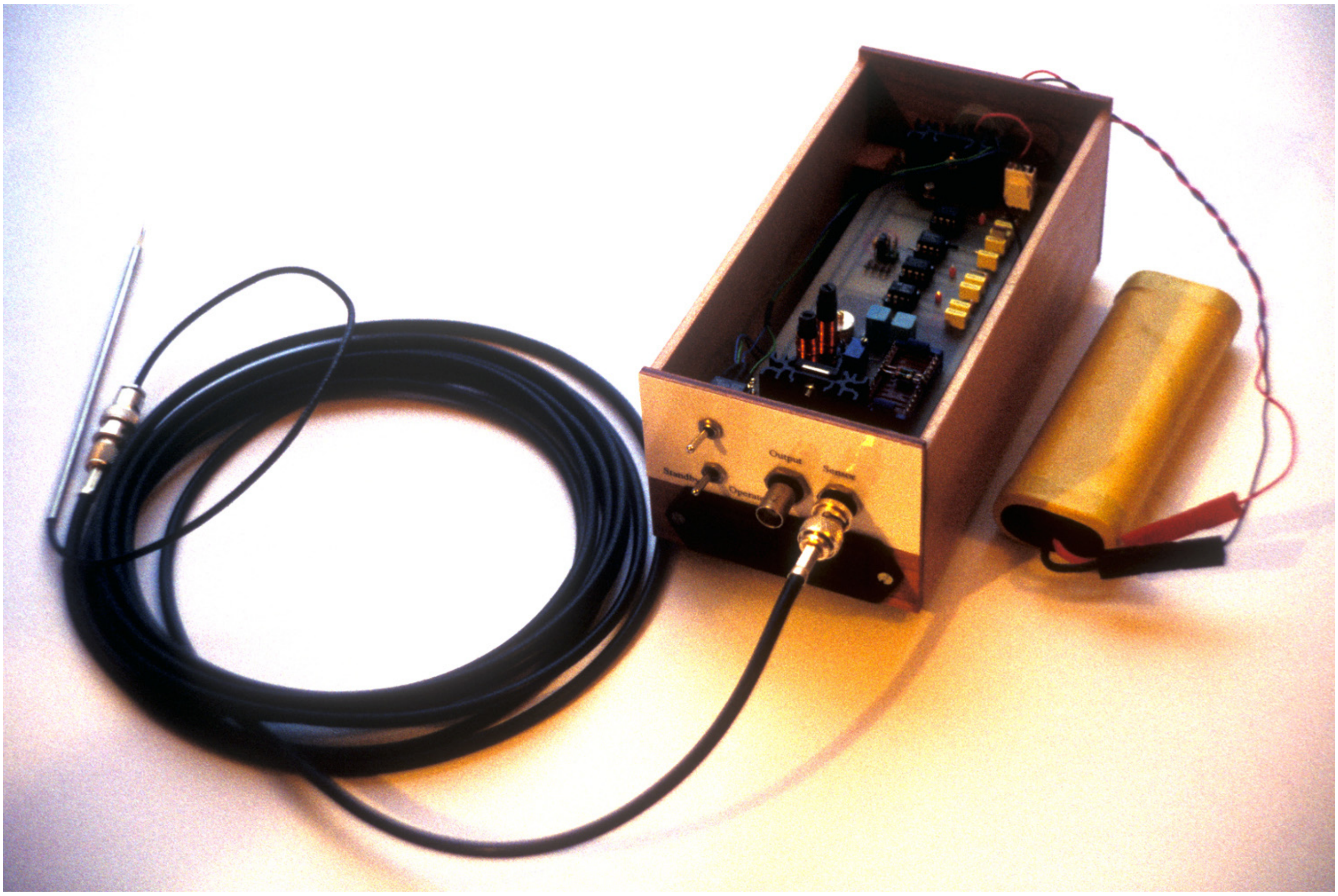


Figure 5. Hot wire anemometer for drag and turbulence measurement.
This is described in detail in appendix A.

Figure 6. Richard in the Markham wind tunnel with the full sized wing section. The hot wire anemometer wake traverse is mounted on the trailing edge. Micro switches limit the travel of the probe and reverse its direction through a flip flop constructed from relays. A drawing of the traverse with some notes is given in appendix B.


Figure 7. A graphical airspeed display. This is nice to use because it shows where you are on the power polar making flying easier. Note I now wonder if an angle of attack display would be better. And if an angle of attack 'hold' autopilot would reduce pilot workload and minimise the power to fly.

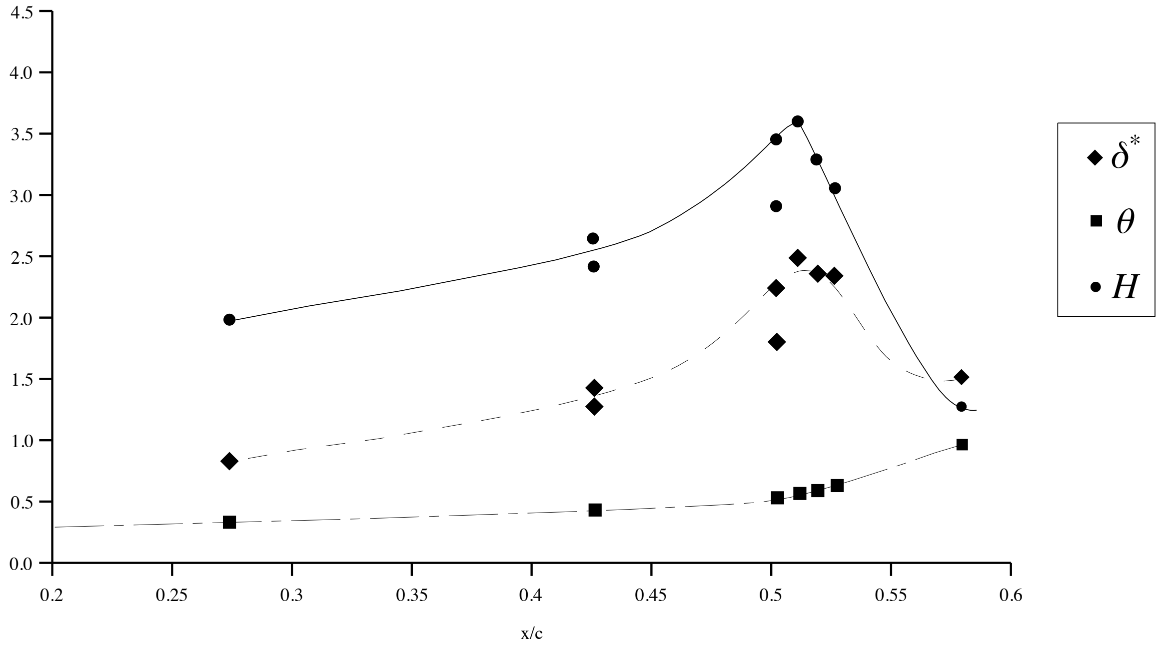



Fig. 8.1 Boundary layer parameters on suction surface at alpha = 0 degrees

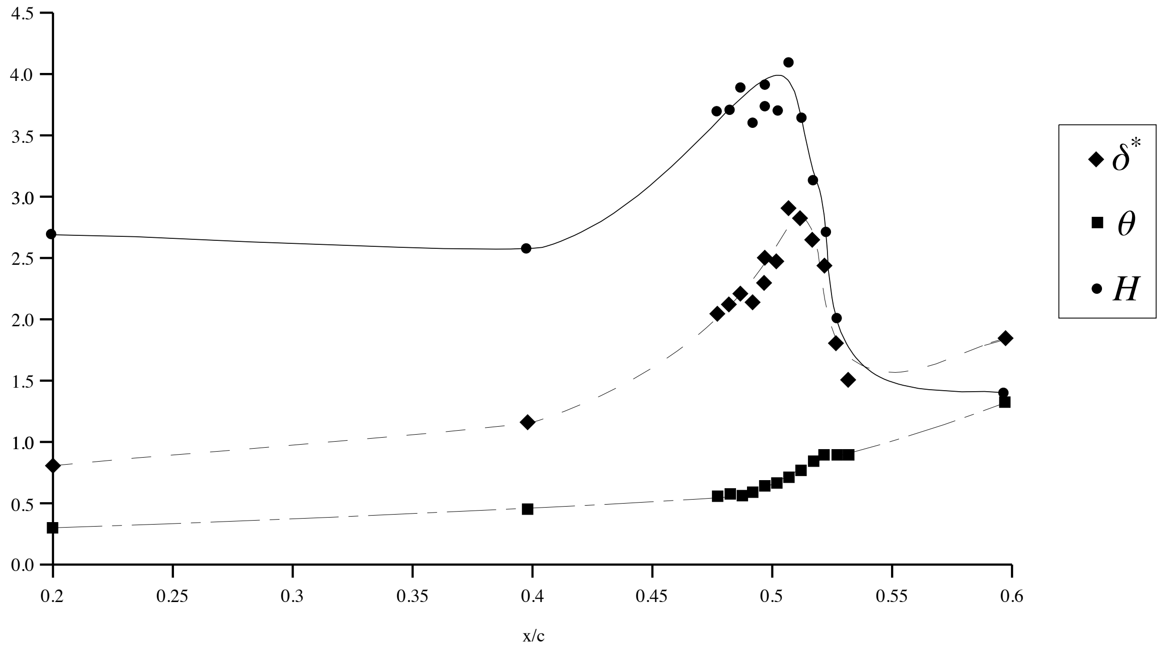



Fig. 8.2 Boundary layer parameters on suction surface at alpha = 4 degrees

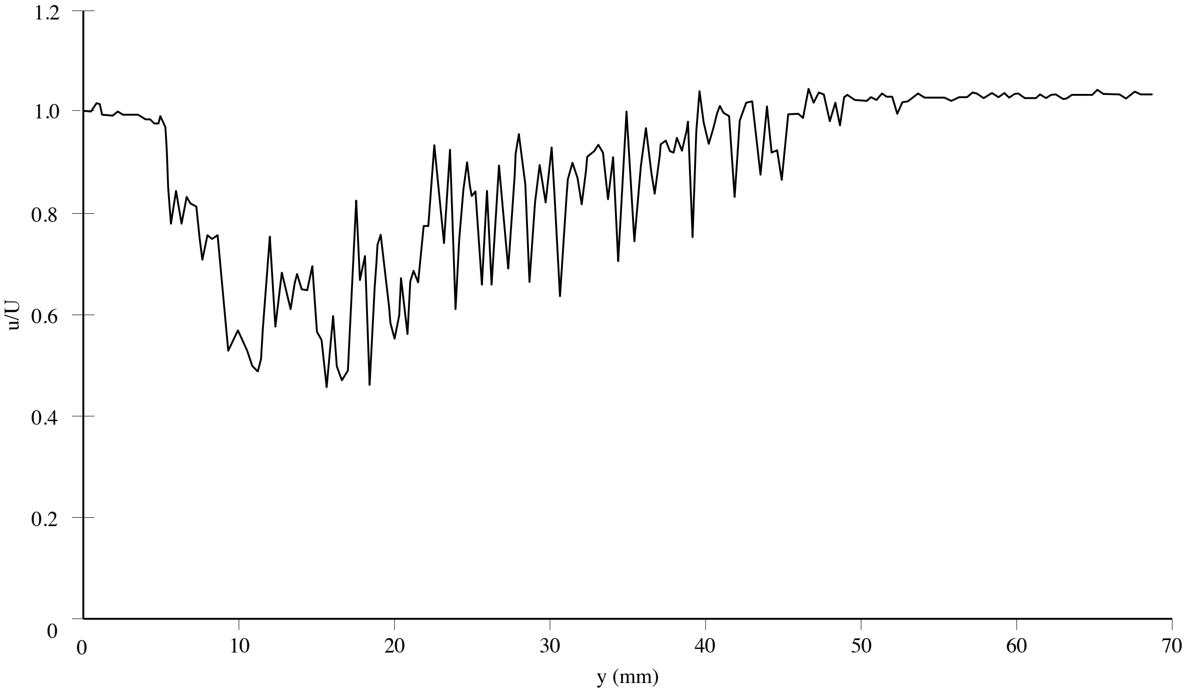



Fig 9.1 Wake profile for alpha = 4, rms free stream turb. Intensity = 0.26%, clean wing. To calculate one drag point several such velocity profiles are averaged.

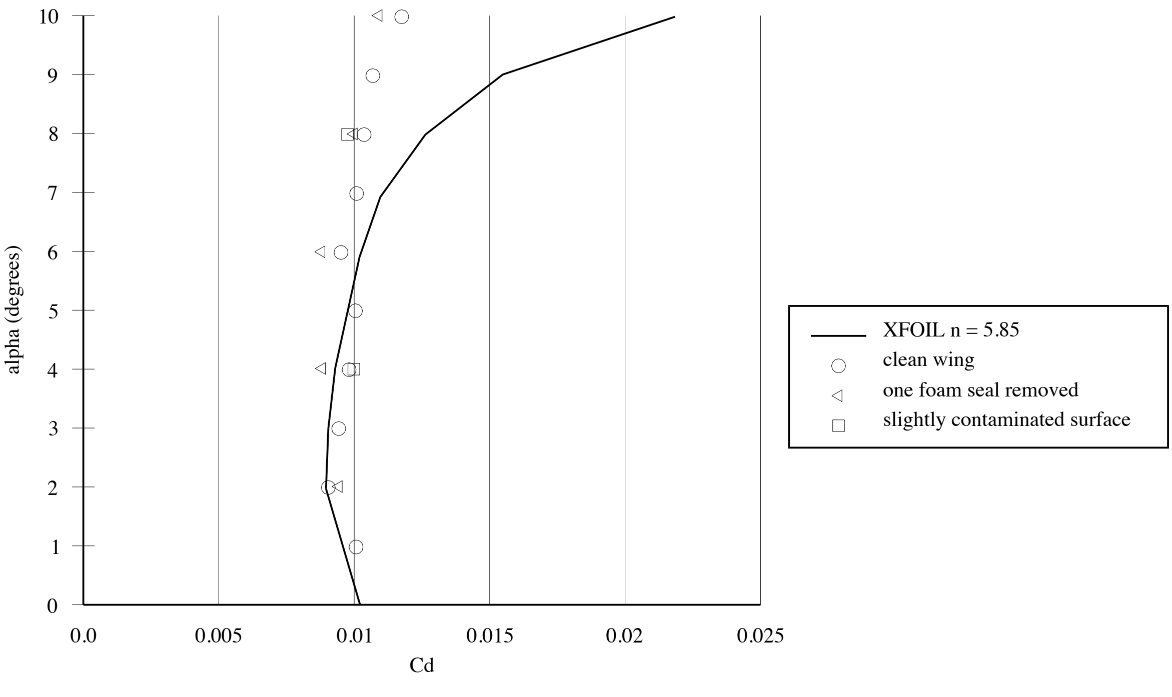



Fig 9.2 Theoretical and experimental drag values for rms free stream turb. Intensity = 0.26%

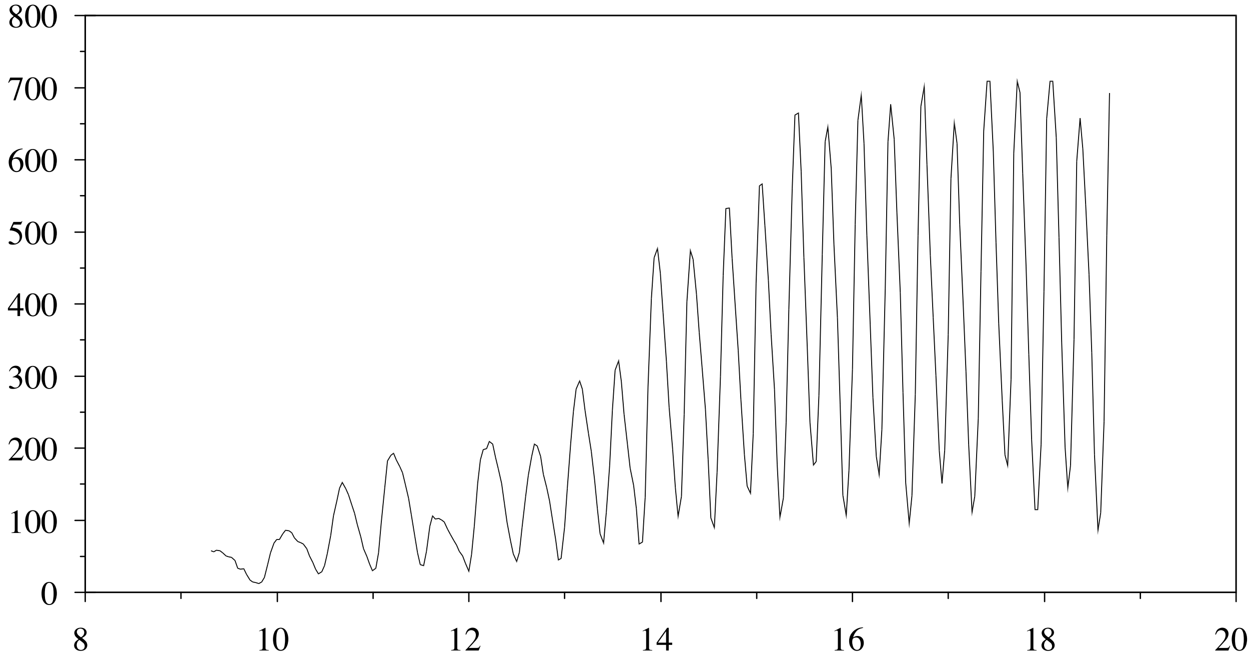



Fig. 10. Power during take off from the power meter.  The raw signal is integrated to optain the average power needed to fly.

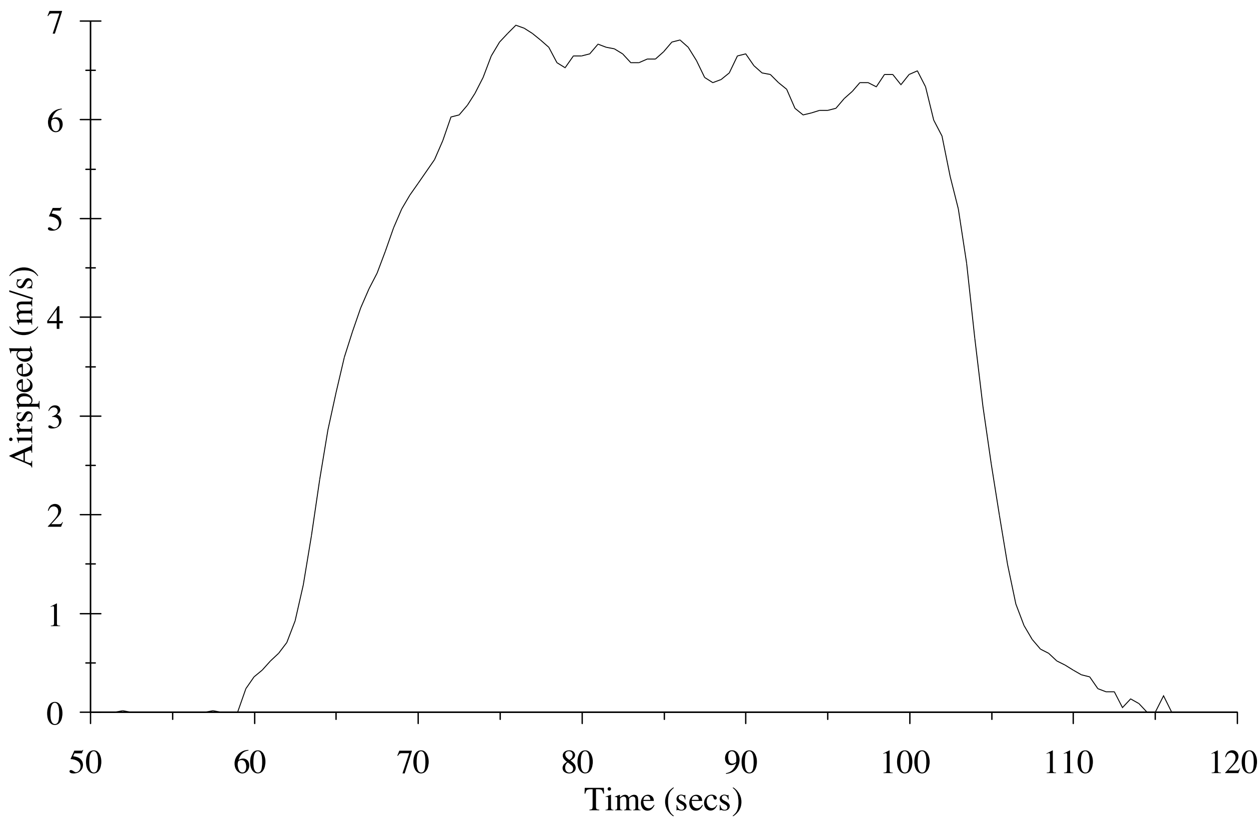



Fig. 11. Airspeed recorded during a short test flight.

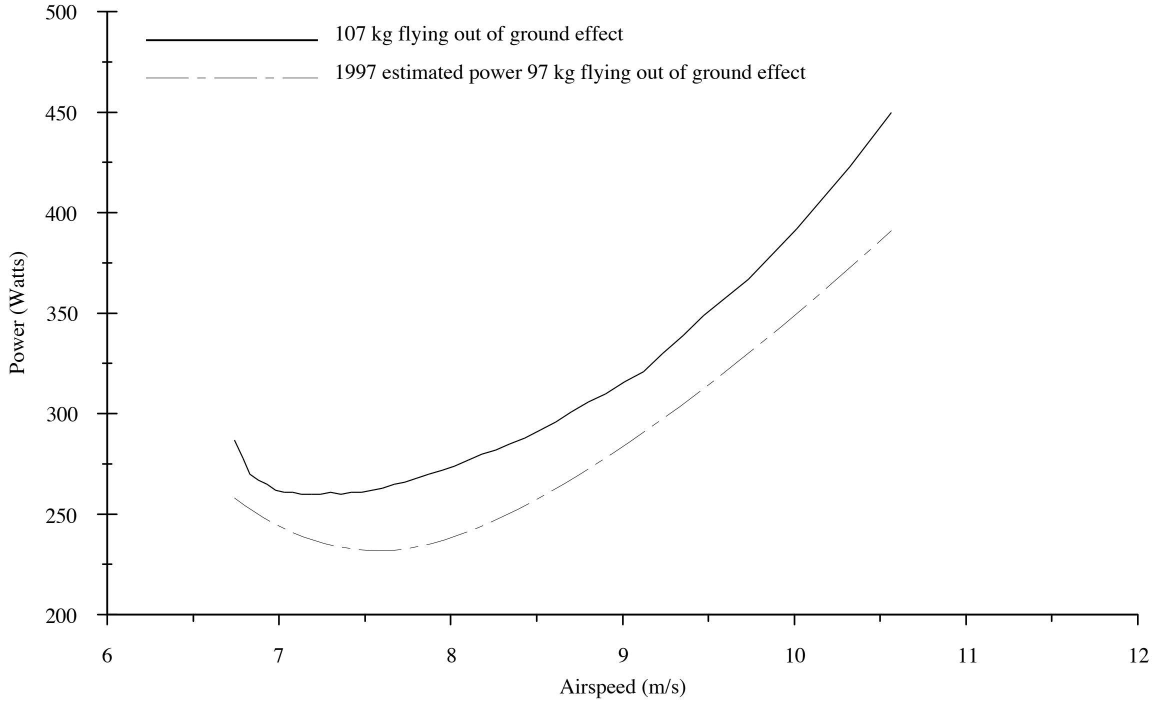



Fig. 12. Power polar calculated in 1995 using a lifting line model and plausible estimateds (I now suspect they were under estimates) and a power polar calculated using a 3d panal code and more detailed estimates for individual componets drag etc.

**Appendix A: Constant temperature hot wire anemometer**

The following schematics and PCB layout are for the CTA we used. The design is by Bryan Gostlow  and has been extensively tested. It could be built smaller and lighter using surface mount components and powered by lithium batteries for flight research. Several versions of power supply have been used. A battery only version that used 9v PP3 batteries for the op amps. A version that used a +- 15v DCDC converter to provide the op amps power supply and a version that used a ‘conventional’ mains power supply with transformers and voltage regulators to use in the wind tunnel.

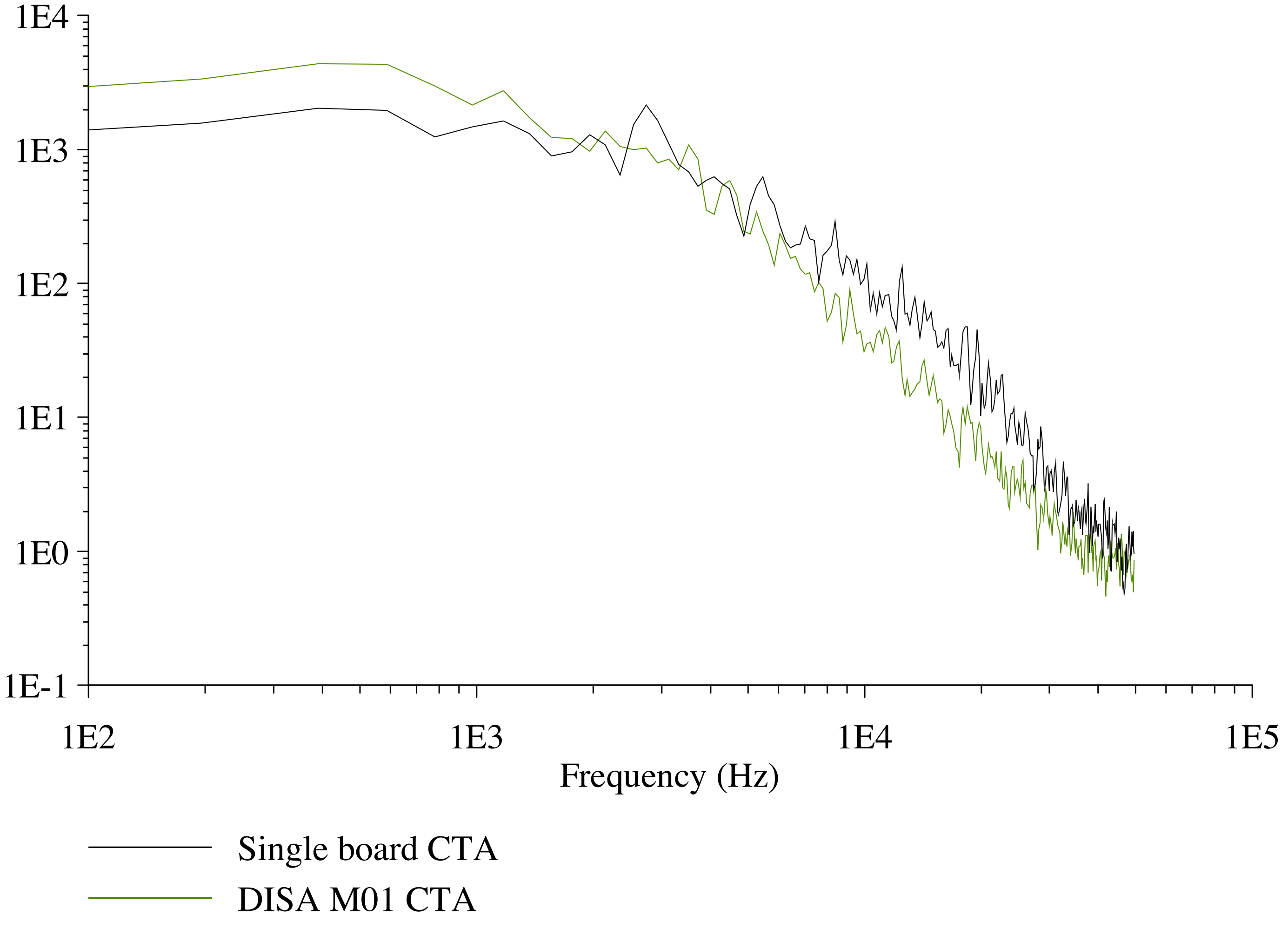
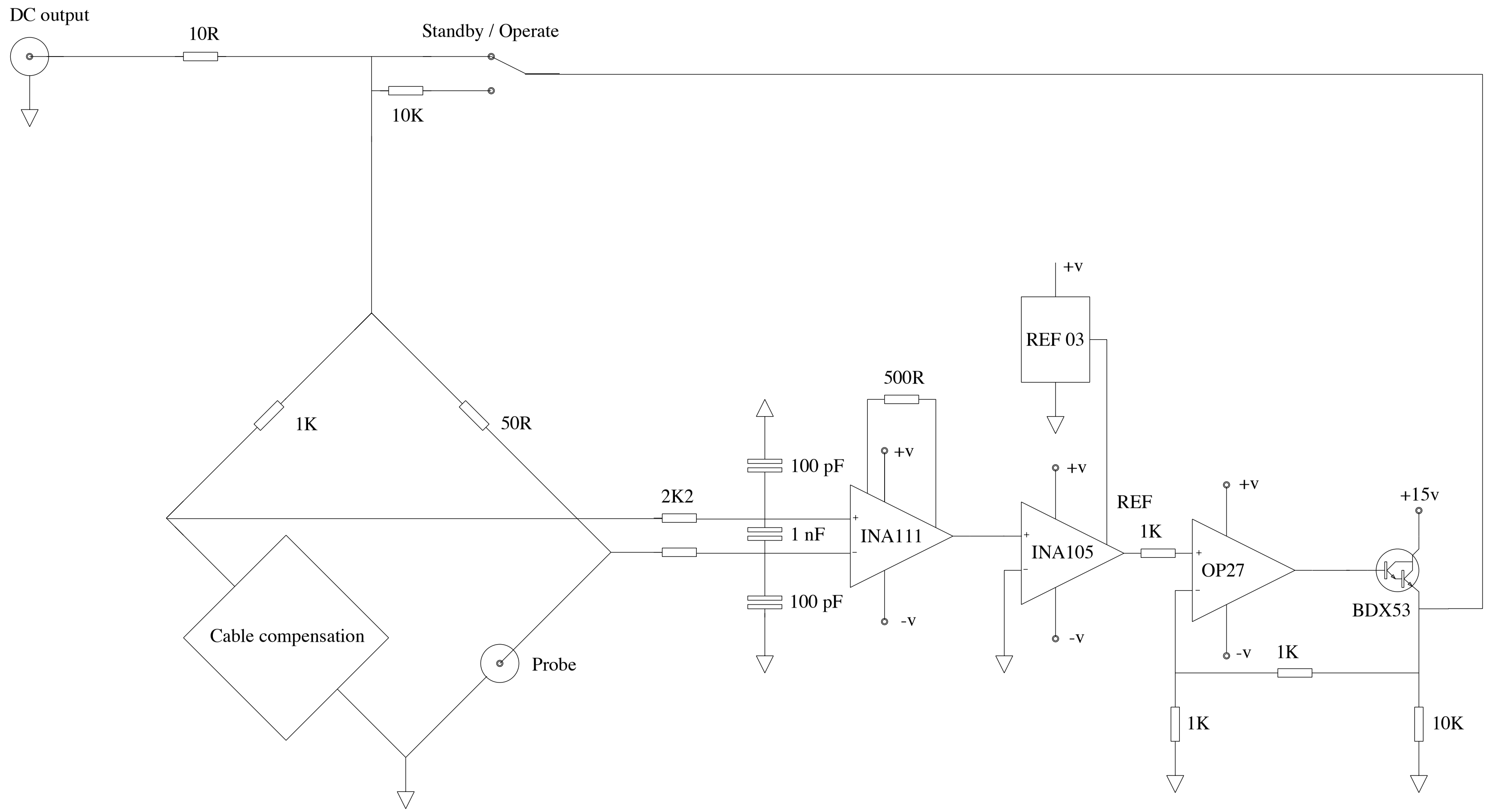
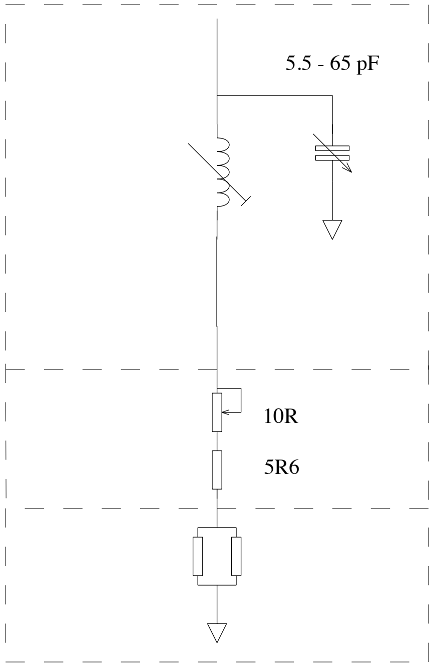



Figure 1. Power spectra of turbulence measured with the single board anemometer.




The ± 15 v power supply for the op amps, voltage reference etc. is separate from the + 15 v bridge supply
Decouple the op amp power supplies with 100 nF capacitors.

5m cable compensation circuit

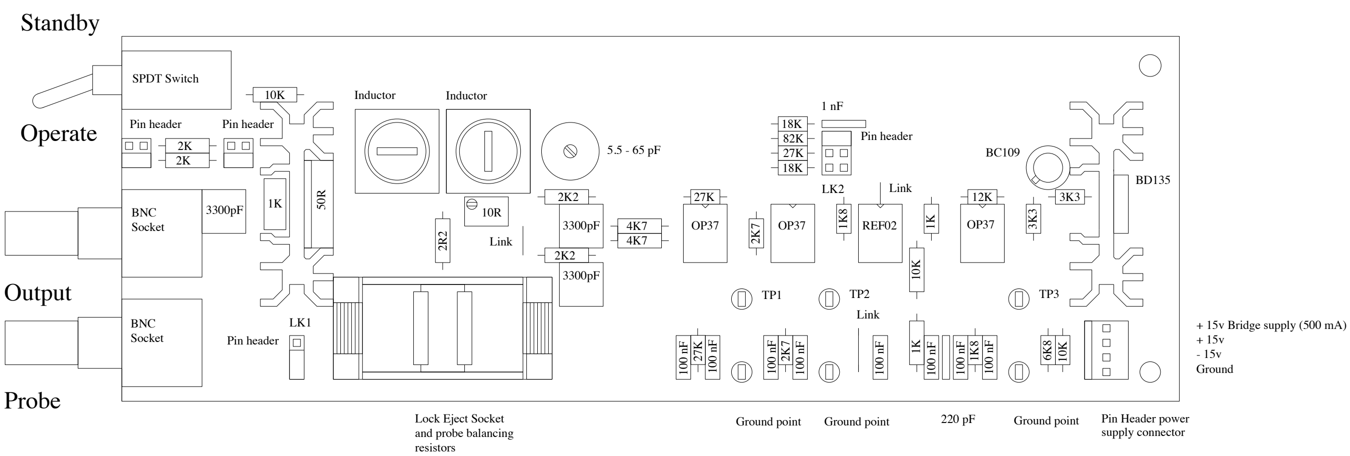



Probe cable inductance compensation

Probe cable resistance compensation

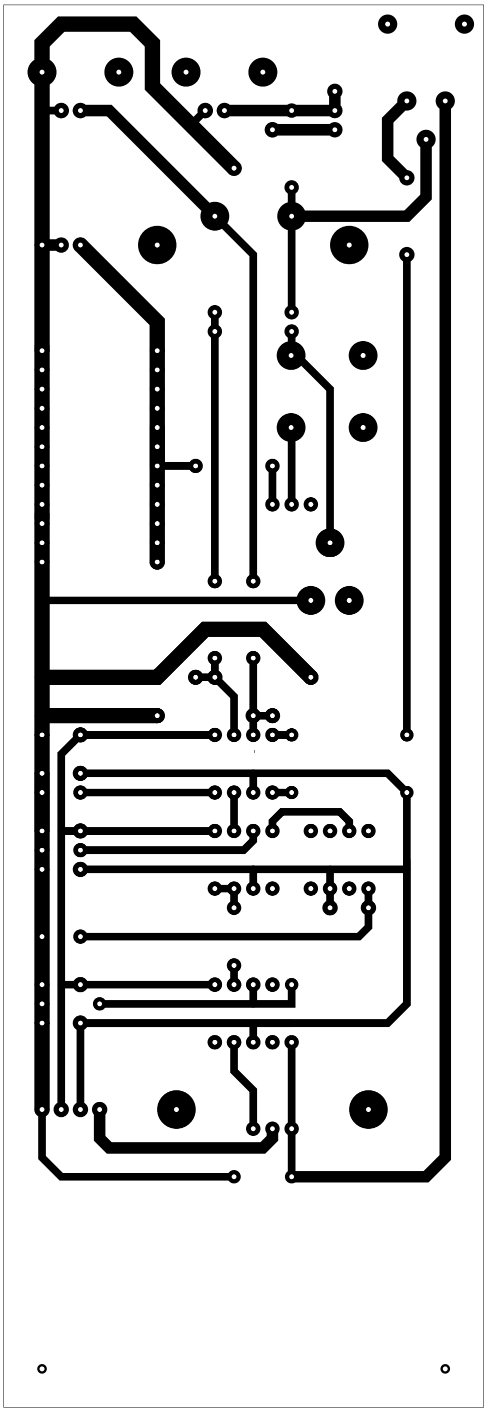
Probe resistance compensation

The variable inductor is made from 60 turns of insulated copper wire wound onto RS coil formers 228-090



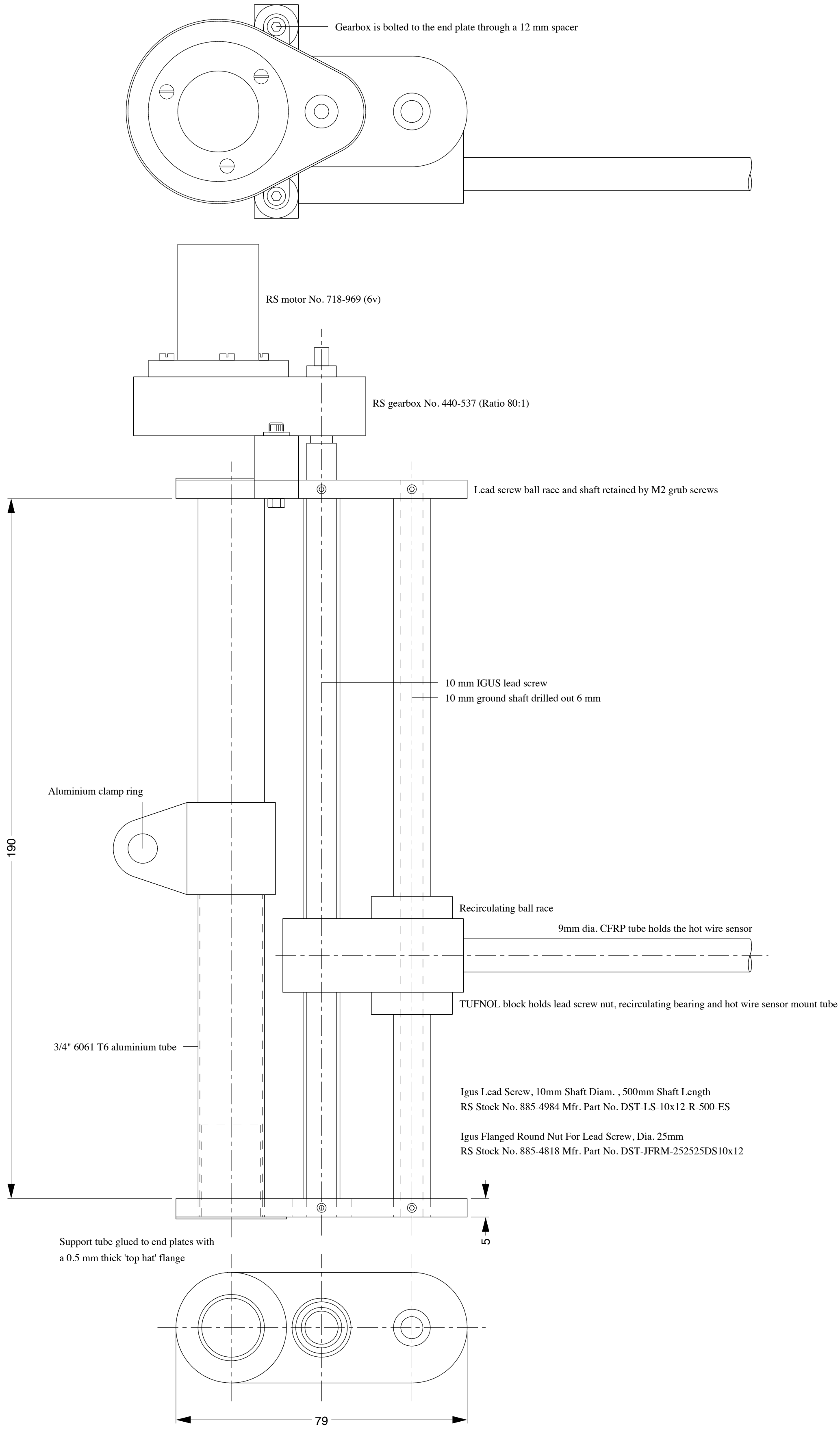

PCB component placement.

PCB



5 m CTA parts

| | | part No. | cost | No off |
|---|---|---|---|---|
| OP37GP | F | OP37GP | £2.78 | 4 |
| 5 v refrence REF 02CP | F | REF02CP | £3.30 | 1 |
| +- 15v regulator | F | RC4195N | 1.63 | 1 |
| + 15v regulator | F | LM340T15 | .60 | 1 |
| BD135 transistor | F | BD135 | .37 | 1 |
| BC107 transistor | F | BC107A-SGS | .31 | 1 |
| | | | | |
| 1% metal film resisters: 50R 1K5 1K8 2K 2K7 3K3 4K7 5K6 6K8 10K 12K 18K 27K | | | | |
| | F | MRS16T + | .054 | 42 |
| 50 R resistor | RHOPOINT | PBH50 | 4.49 | 1 |
| 1K precision resistor | F | RC55 + 1K | .70 | 1 |
| 3/8” 10R trimmer | RS | 160-001 | 1.02 | 1 |
| 100 nF decoupling capacitor | F | 146-079 | .10 | 18 |
| 100 nF capacitor for 2nd OP amp | RS | 126-556 | .26 | 1 |
| 220 pF capacitor | F | 237-050 | .09 | 1 |
| 3300 pF capacitor (filter) | F | 106-069 | .33 | 4 |
| 10 uF 22v capacitor (power supply) | F †† | 227-869 | .33 | 3 |
| 5.5 - 65 pF capacitor | F | 808-32659 | .21 | 1 |
| 8 way dill socket | F | 178-827 | 4.70/20 | 6 |
| 16 way dill socket | F | 178-829 | 4.89/10 | 1 |
| 24 way dill socket | F | 176-364 | 1.41 | 1 |
| 24 way eject socket | F | 177-819 | 2.20 | 1 |
| SPDT pcb mounting switch | F | 146-238 | 2.57 | 1 |
| Insulated 90 degree PCB BNC socket | F | 149-859 | 2.04 | 3 |
| Pannel nuts for above socket | F | 149-916 | .30 | 3 |
| Coil formers | RS | 228-090 | 2.36/5 | 2 |
| Ferite cores | RS | 228-107 | 2.90/10 | 2 |
| Pin header | F | 148-194 | 1.16 | 1 |
| Jumper | F | 148-029 | .17 | 4 |
| 8 dill switch | F | 148-461 | 2.79 | 1 |
| 4 dill switch | F | 148-460 | 1.66 | 1 |
| Heat sink | F | 175-650 | .63 | 3 |
| Test points | F | 240-345 | 5.60/100 | |
| Mounting brackets for inductor PCB | F | MP5012 | 3.07/10 | |
| Transistor mounting bolts | F | 170-020 | .88/10 | |
| Transformer 30VA 18V | F | 177-955 | 11.33 | 1 |
| ** 15v ** ERROR | | | | |
| Rectifier | RS | 630-803 | .90 | 1 |
| 2000 uF capacitpr | RS | 394-844 | 4.35/5 | 2 |
| Filter plug | F | 237-293 | 7.28 | 1 |
| Fuse holder | F | 319-340 | 1.23 | 1 |
| Switch | F | 273-168 | .68 | 1 |
| LED (FEC p 518) | F | 264-362 | .30 | 1 |
| Panel plug | F | 212-003 | 2.93 | 1 |
| Free socket | F | 211-990 | 7.28 | 1 |
| | | | | |
| Total (Note 1995 prices) | | | 96.04 | |




Appendix B. Drawing of the wake traverse used to measure drag in a wind tunnel and in flight. This drawing was drawn full sized and scaled to fit here. A few dimensions are given for anyone wishing to copy it. Note. Many CAD programs will import pdf format so it is easy to import this drawing and scale it back up to full size.